Capacitive-sharing Readout Structures For MPGDs

Preliminary results from Hall D beam test @ JLab 2021

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RD51 Collaboration Meeting – November 17th, 2021

Outline

- Concept of capacitive-sharing readout structures: R&D and prototypes
- Preliminary results of µRWELL prototype with capacitive-sharing strip readout
- New capacitive-sharing structures under development

Concept of capacitive-sharing readout: R&D & prototypes

Capacitive-sharing readout: Principe & Motivation

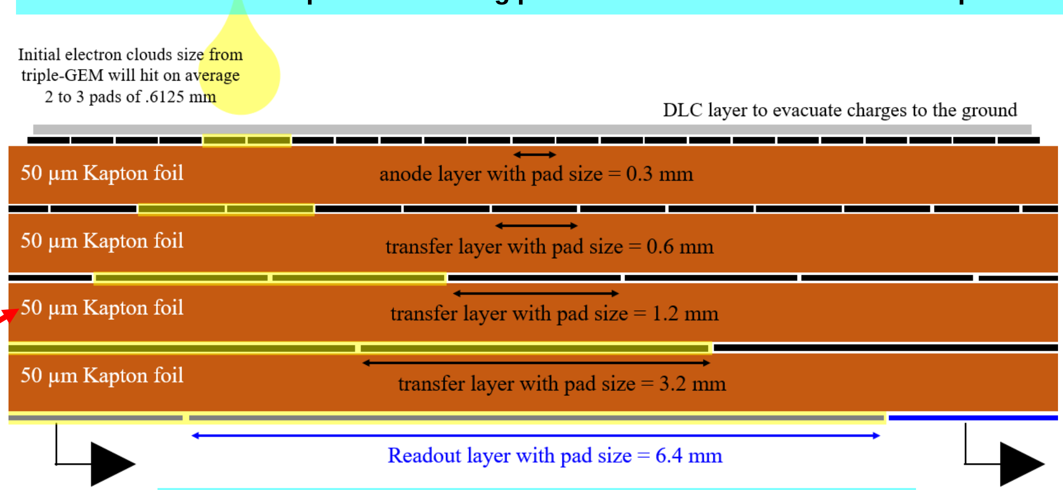
Principe of capacitive-sharing readout structures:

- Vertical stack of pads layers ⇨ Transfer of charge from MPGD via **capacitive coupling**
- A given arrangement of the pads position from one layer to the layer underneath as well as the doubling in size of the pad pitch allows:
  - Transverse sharing of the charges between neighboring pads of the layer (i+1) from vertical charged transfer from layer (i) through capacitive coupling
  - Principle of transverse charge-sharing through capacitive coupling i.e., **capacitive-sharing** is illustrated on the cross-section sketch on the left
- The scheme preserves of the position information i.e. spatial resolution with large readout strips or pads ➔ Goal 50 µm for 1-mm strip r/o and 150 µm for 1 cm² pad r/o
- Basic proof of concept established with **800 µm** X-Y strip and ***1 cm²*** pad readout

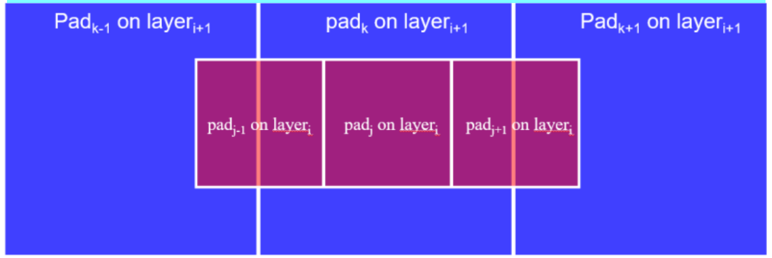
Motivation & some key facts of capacitive-sharing readout:

- Develop high performance & low channel count readout structures for MPGDs:
  - Reduce the number of readout electronic channels for large area MPGDs
  - Low-cost technology for large area ➔ standard PCB fabrication techniques
  - Application for future colliders and NP experiments (See F. Bossu's talk on Tuesday)
- Capacitive-sharing concept is **simple, versatile and flexible**:
  - Compatible with all MPGD technologies ➔ GEM, uRWELL, Micromegas, THGEM …
  - Compatible with all type of readouts ➔ pads, 2D-strips, zigzag, 3-axis X-Y-U etc …

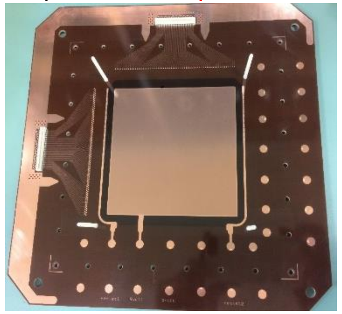
Cross section of capacitive-sharing pad readout with 6.4 mm × 6.4 mm pads



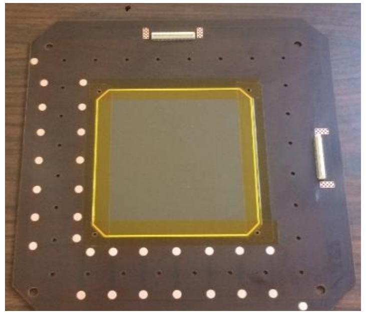
Top view of two pad-sharing layers



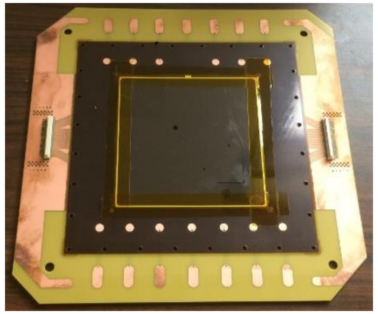
capaSh-XY-Strip uRWELL



capaSh-XY-Strip GEM



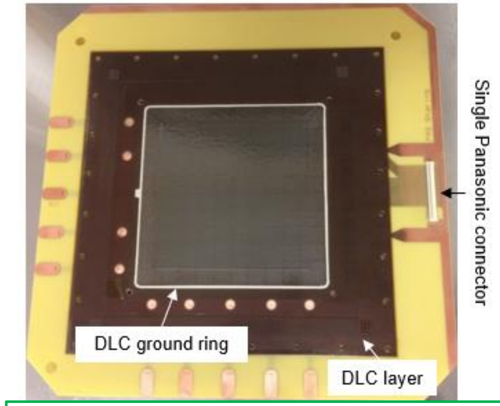
capaSh-Pad GEM

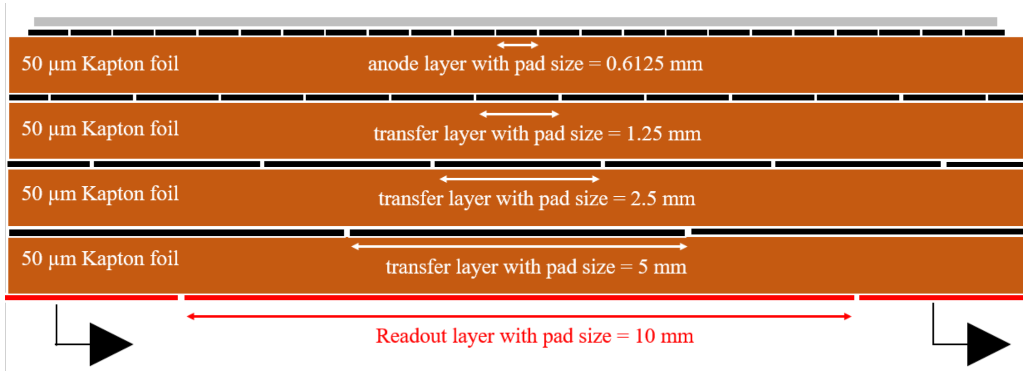


Proof of concept with 1-cm^2 pad readout GEM proto (2020)

University of Virginia — Jefferson Lab, Exploring the Nature of Matter

Readout pad Layer: 1 cm × 1 cm pads





First capacitive-sharing proto tested with standard triple-GEM to demonstrate the proof of concept:

- DLC layer surface resistivity 10-20 MΩ, 4 capacitive-sharing layers (black pads), r/o pad layer (red pads
- Top pad: 0.625 mm × 0.625 mm & r/o pads: 1 cm × 1 cm ➔ total 100 r/o channels to readout
- 2 new protos with 9 mm x 9 mm and 6.4 mm x 6.4 mm
  - tested @ Fermilab May 2021 ➔ analysis ongoing

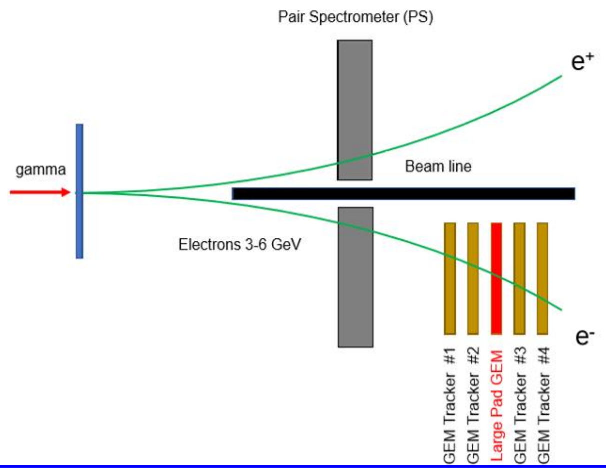
Beam test setup in Hall D @ JLab (2020):

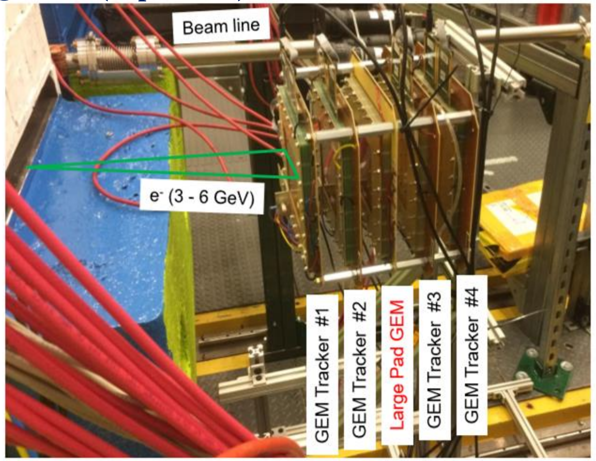
- 1 cm × 1 cm pad capacitive-sharing GE< + 3 X-Y COMPASS GEMs for precise tracking
- Hall D pair spectrometer beam: 3 - 6 GeV electron beam, tracks angle from reconstruction**: 7 deg in x and 2 deg in y**

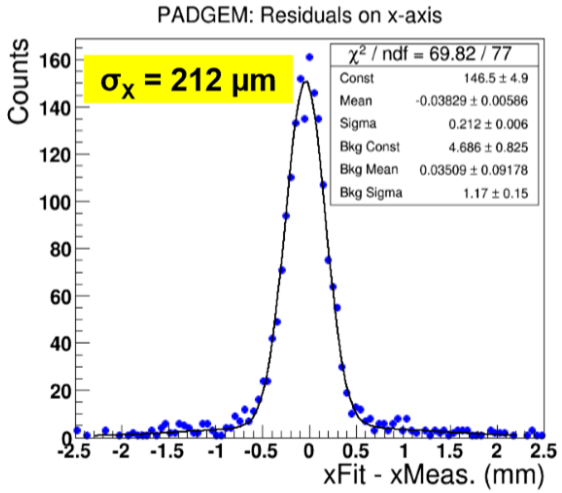
Performances:

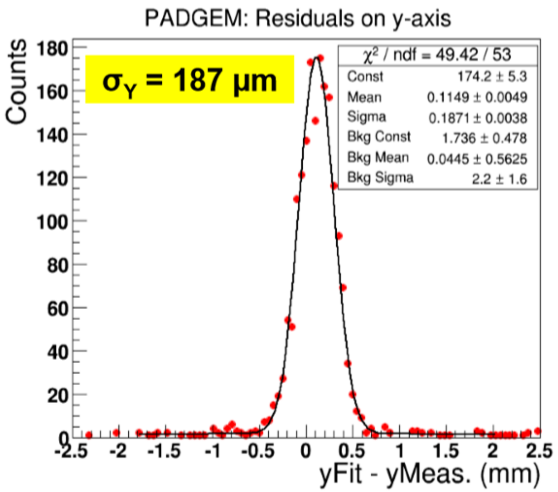
- Spatial resolution **212 µm and 187 µm** in x and y respectively
- slightly worse in x ➔ incoming track angle effect
- Results obtained from track fit from COMPASS GEM ➔ but with no alignment correction
  - Expect improvement of the spatial resolution after tracking alignment are implemented

Beam test setup in Hall D @ JLab (Sept. 2020)





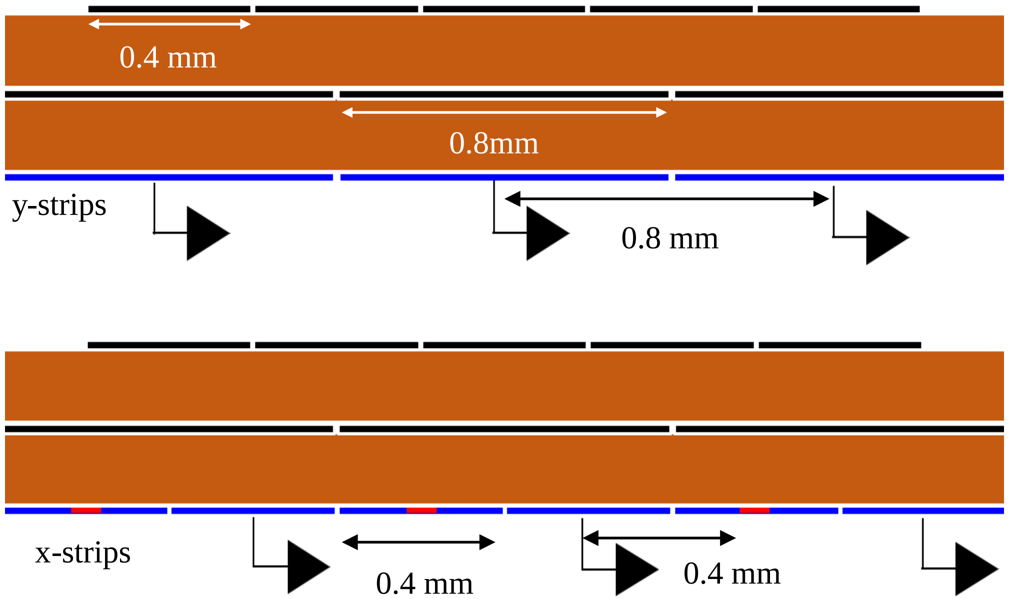


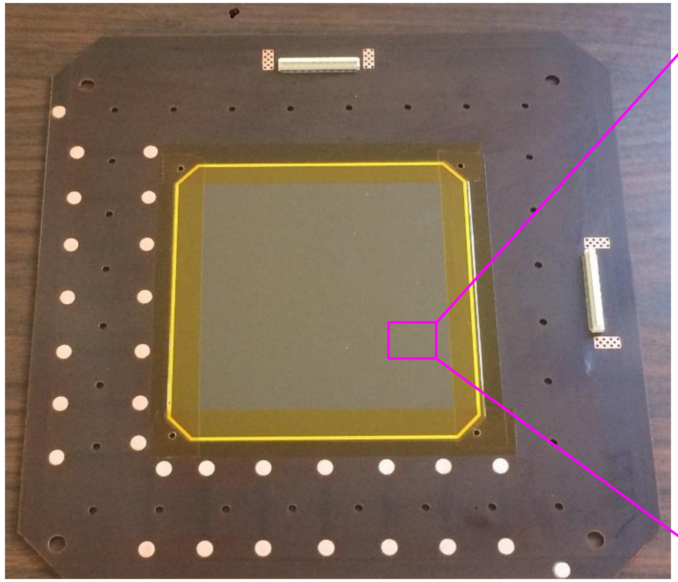


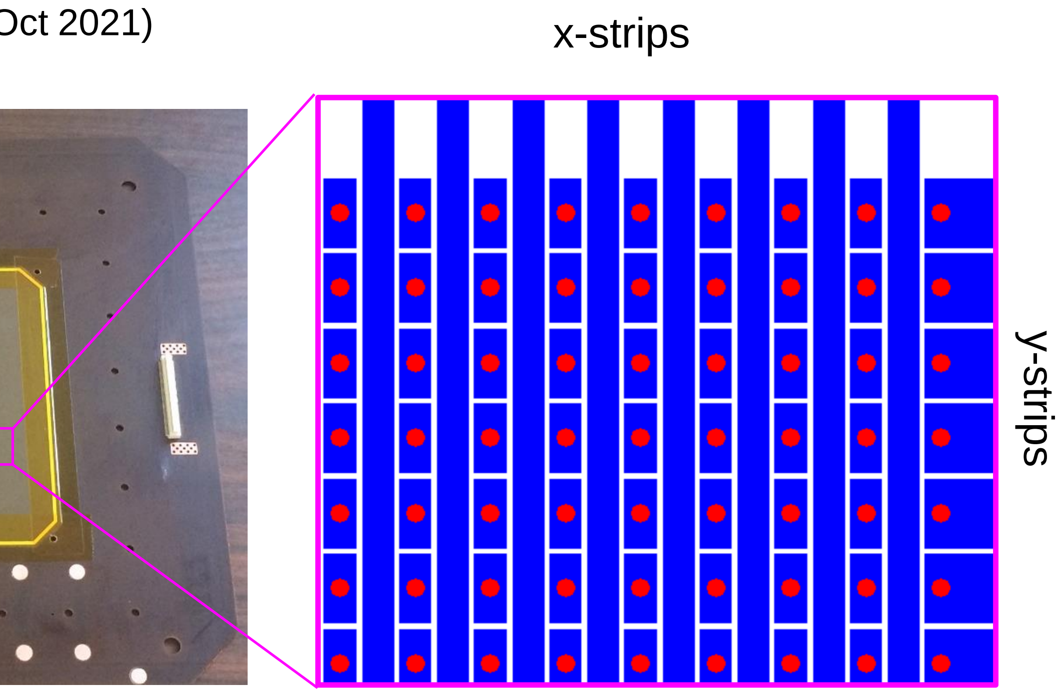
Capacitive-sharing **X-Y strip** readout: GEM prototype

Standard 10 cm × 10 cm CERN triple-GEM with capacitive-sharing 2D strip readout

- Pitch is 800 µm ➔ twice COMPASS readout strip design
- **X-strip and Y pad-like strips design** with the 2 sets of strips on same layer ➔ guarantee equal charge sharing between X-Y strips
  - Width of x-strips = 350 µm
  - Pad size of the pad-like strips = 350 µm × 750 µm
  - pad-like strip are connected through vias on a layer below
- 2 capacitive-sharing pad layers with: 400 µm and 800 µm pad size respectively
- Tested in hadron beam test at FNAL (May 2021) and electron Hall D @ JLab (Sept-Oct 2021)



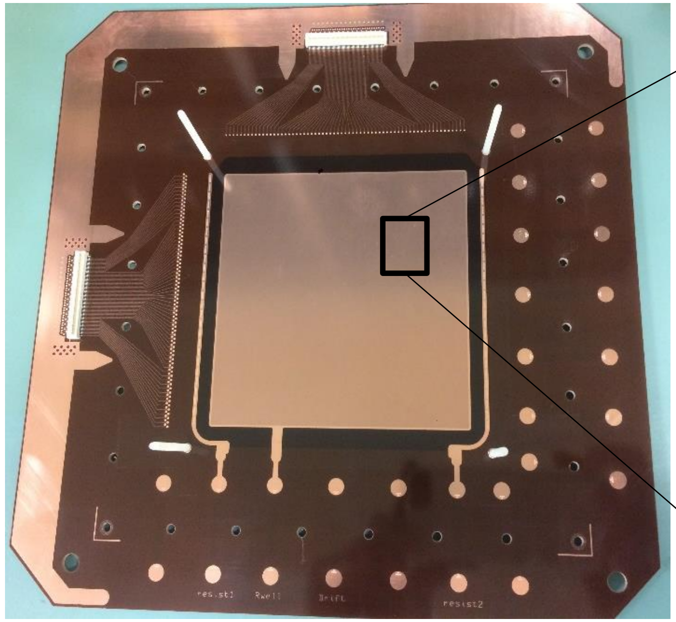


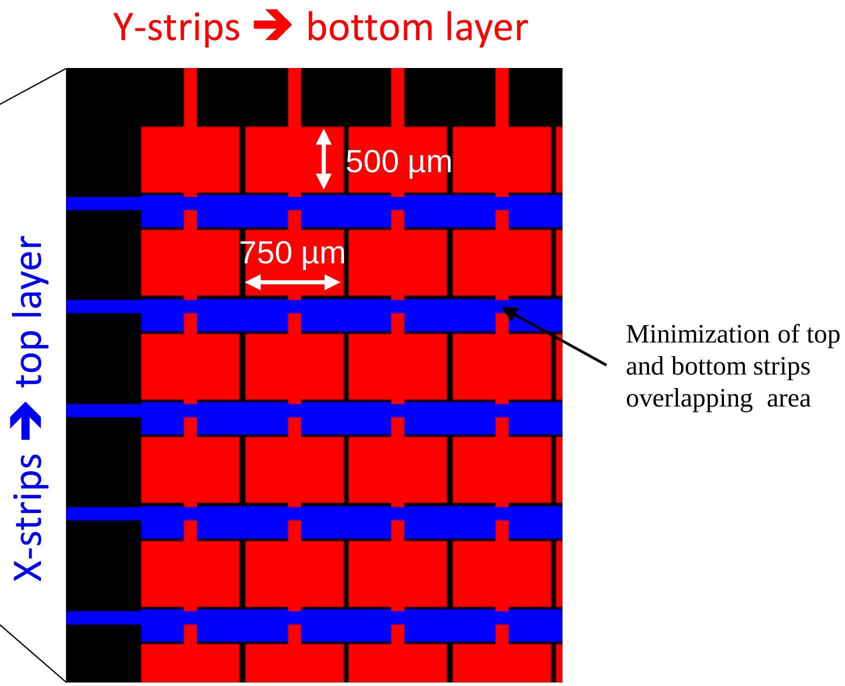


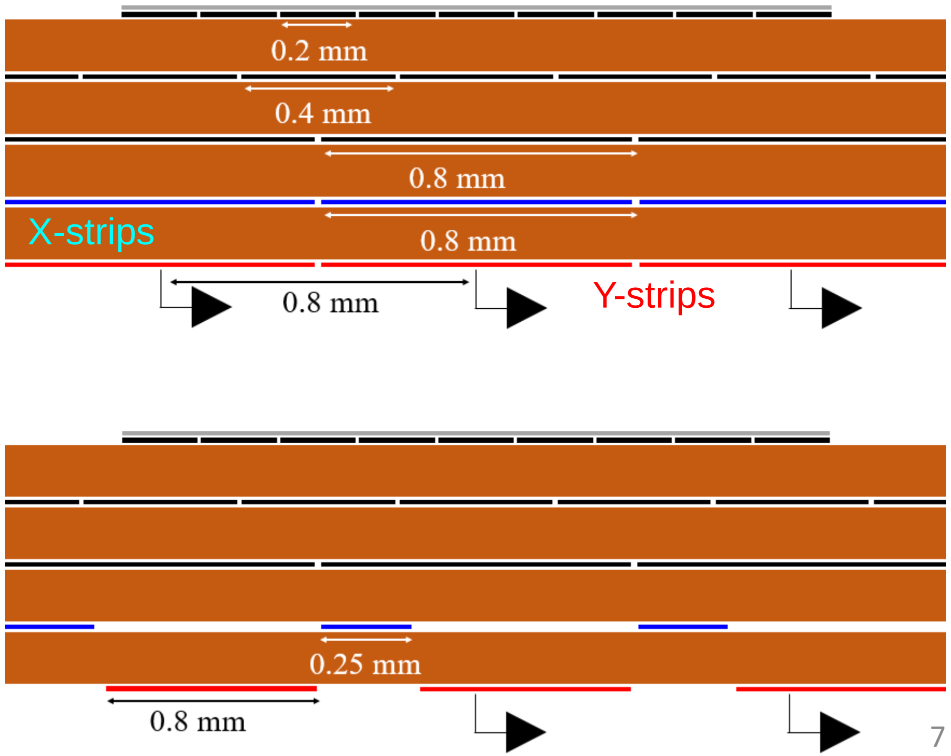
Capacitive-sharing **X-Y strip** readout: µRWELL prototype

10 cm × 10 cm µRWELL with capacitive-sharing 2D strip readout

- Pitch is 800 µm ➔ twice COMPASS readout strip design
- X-strip and Y-strips on two separate layers with No connecting vias ➔ Easy fabrication for large area, low-mass capability
- Strip parameters: top strip (y-strips) = 250 µm, bot strip (x-strips): 750 um × 500 µm ➔ require tuning for equal charge sharing
  - Top and bottom strip area overlap minimized by design to minimize cross talk and capacitance etc …
- 3 capacitive-sharing pad layers with: 200 µm, 400 µm and 800 µm pad size respectively
- Tested in electron beam in Hall D @ JLab (Sept-Oct 2021)



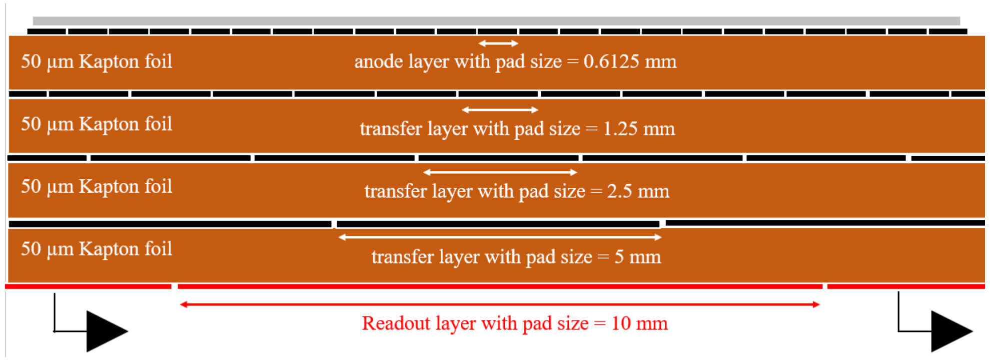




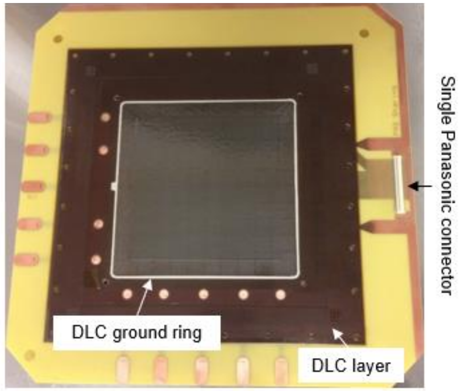
Couple of capacitive-sharing **Pads** readout: with GEMs

3 capacitive-sharing pad readout with standard triple-GEM amplification

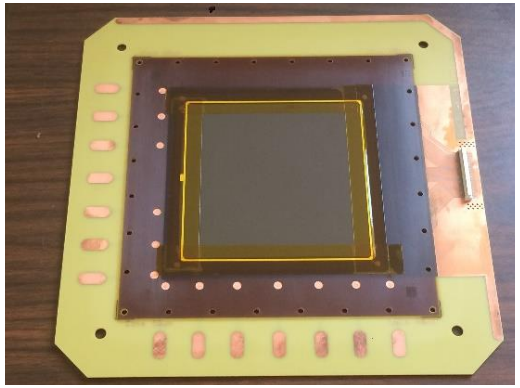
- All 3 have 5 pad-layers configuration: DLC with surface resistivity 10 - 20 MΩ, + 4 capacitive-sharing layers (black pads) + r/o pad layer (red pads)
- **10 mm proto:** top layer pad: 0.625 mm × 0.625 mm & readout layer pads: 10 mm × 10 mm ➔ total 100 r/o channels to readout
- **9 mm proto:** top layer pad: 0.5625 mm × 0.5625 mm & readout layer pads: 9 mm × 9 mm ➔ total 121 r/o channels to readout
  - Active area divided in 4 quadrants with different inter gap pads (applied to all 5 layers)
  - Want to study impact of the inter gap on spatial resolution performance
- **6.4 mm proto:** top layer pad: 0.4 mm × 0.4 mm & readout layer pads: 6.4 mm × 6.4 mm ➔ total 256 r/o channels to readout
- All 3 prototypes have been tested in proton beam at FNAL (May 2021) ➔ Analysis of the data is ongoing …



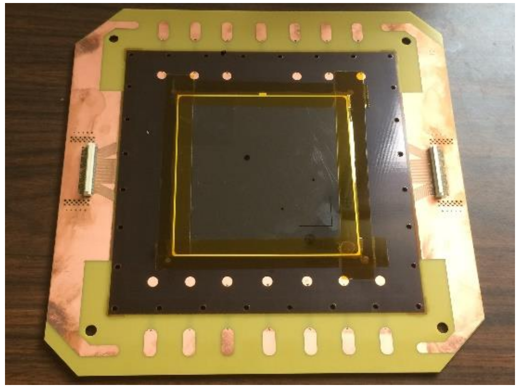
GEM w/ 10 mm C-Sh pads



GEM w/ 9 mm C-Sh pads



GEM w/ 6.4 mm C-Sh pads



Beam test results of **µRWELL** prototype with capacitive-sharing X-Y strips readout

Beam test in Hall D @ JLab

Beam test setup in Hall D @ JLab (2021):

- ❖ Hall D pair spectrometer: 3 - 6 GeV clean electron beam
- ❖ Two capacitive-readout X-Y strips (µRWELL and GEM) prototypes in tests
- ❖ 4 X-Y COMPASS GEMs for precise tracking
- ❖ Standard APV25-SRS readout with standard DATE and amoreSRS DAQ
- ❖ All detectors runs with Ar-CO2 (80/20) ➔ **HV on µRWELL from 550 V to 580 V**

❖ **Capacitive-sharing X-Y µRWELL proto:**

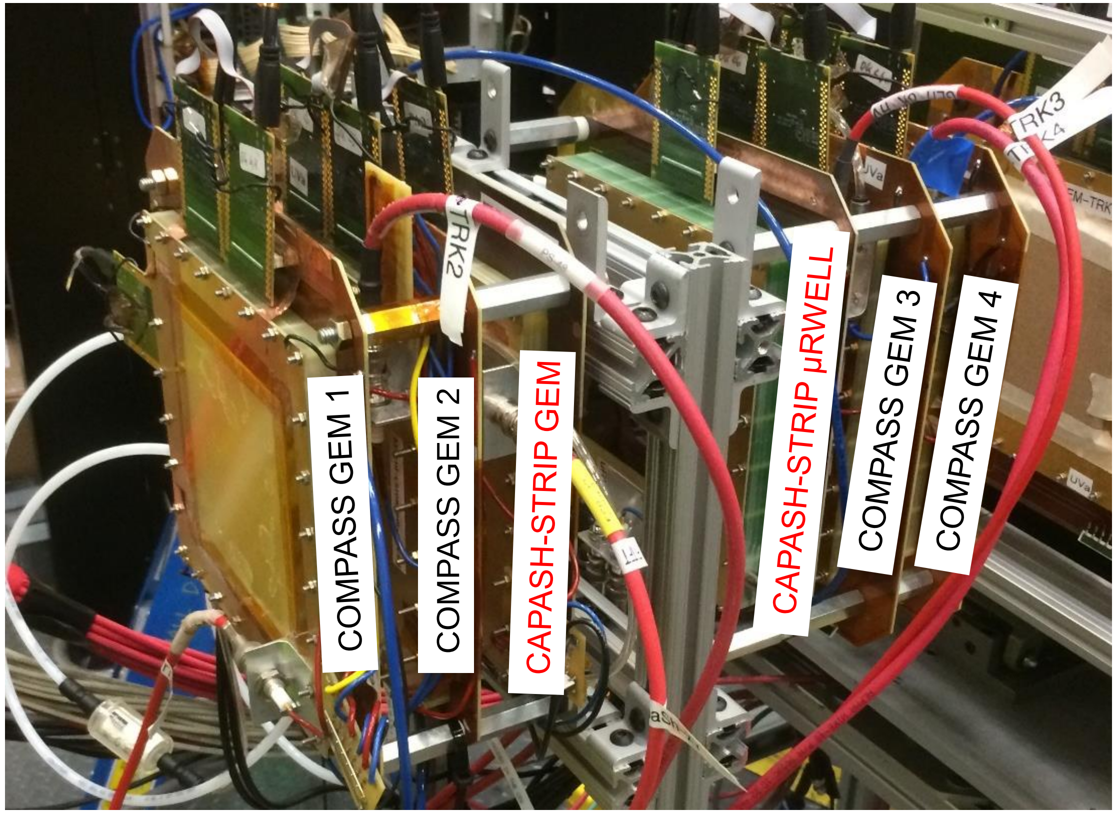
- ❖ HV scan for the field in the ionization / drift region
- ❖ HV scan for µRWELL amplification
- ❖ Study cluster size, gain, spatial resolution vs. HV scan for capacitive-sharing readout

❖ **Capacitive-sharing X-Y GEM proto:**

- ❖ HV scan for GEM amplification
- ❖ Study cluster size, gain, spatial resolution vs. HV scan for capacitive-sharing readout
- ❖ Confirm equal sharing
- ❖ Compare GEM performance with µRWELL

❖ **Preliminary results with µRWELL:**

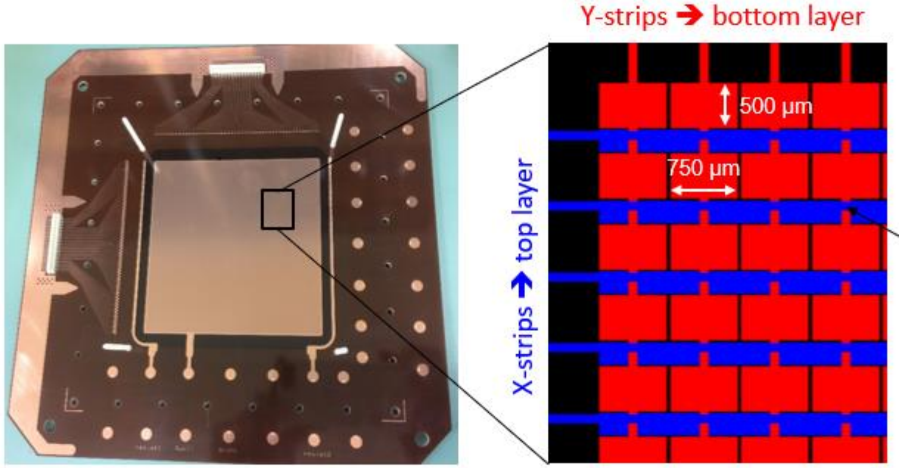
- ❖ COMPASS GEM telescope provide track fit for spatial resolution & efficiency analysis
- ❖ Results presented today are **very preliminary and with µRWELL** proto only
  - ❖ No alignment correction applied to the spatial resolution analysis ➔ residuals plots presented (not intrinsic resolution)
  - ❖ Expect dramatic improvement of the spatial resolution performance after tracking alignment correction are implemented

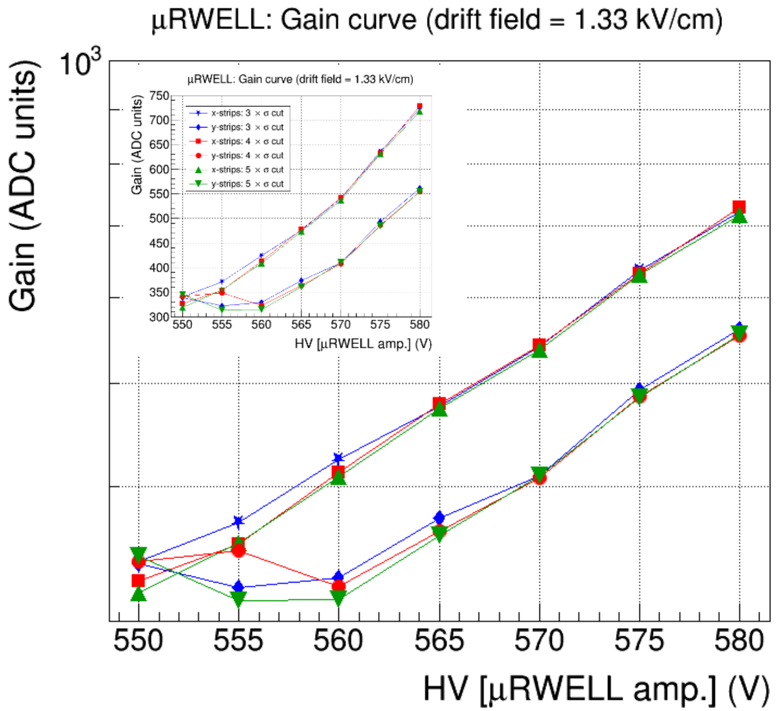


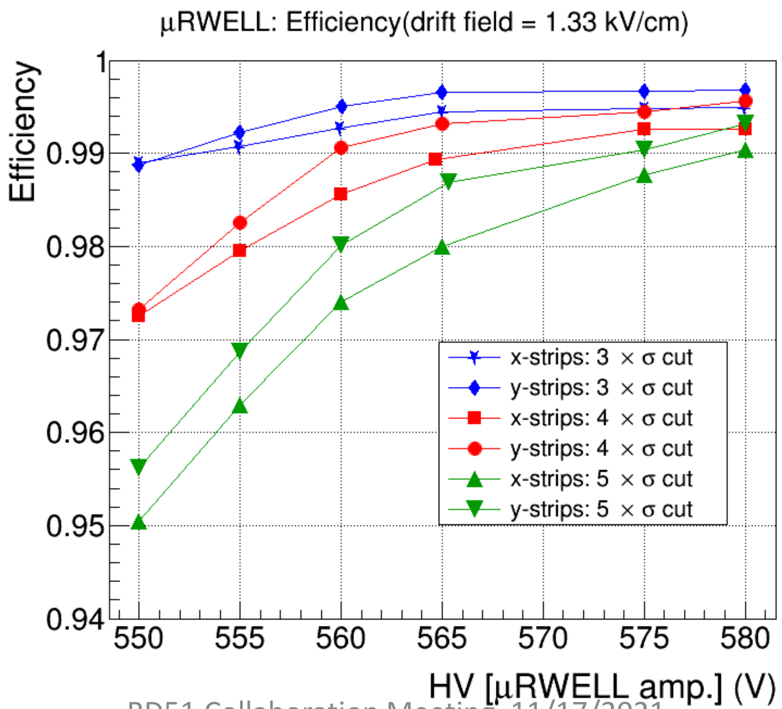
Preliminary results: µRWELL Gain & Efficiency

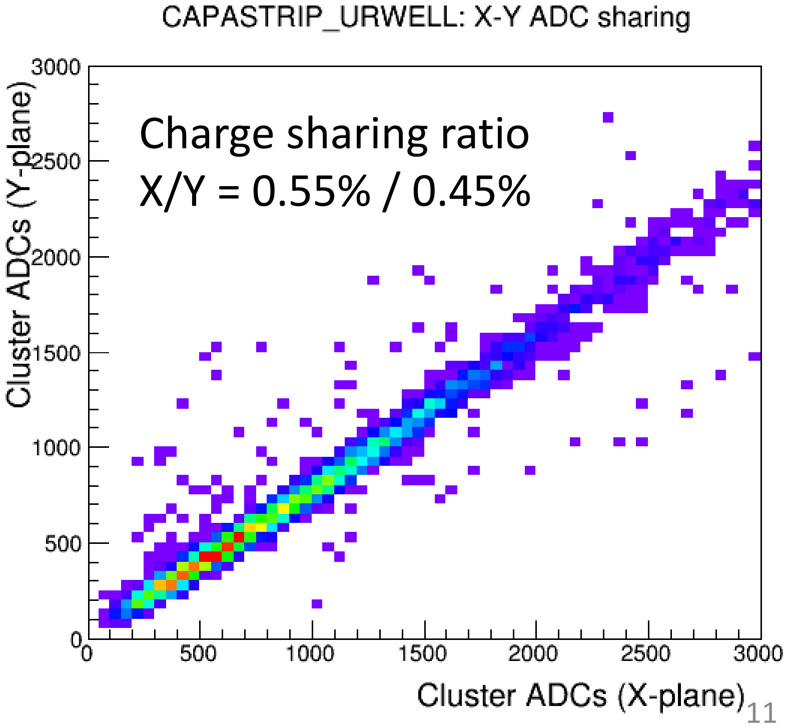
Capacitive-sharing X-Y µRWELL proto: with Ar-CO2 (80/20)

- HV on µRWELL (amplification) from 550 V to 580 V ➔ very stable operation in all HV settings
  - Did not go higher because the signal on APV was already large enough
  - Did not go lower than 540 V to not waste beam time
- Efficiency > 95% for 550 V and > 99% for 580 even at 5 × σ pedestal cut
  - Minimum 2-hit cluster requirements for a good event
- X/Y charge sharing ratio: ~ 0.55 / 0.45 ➔ mostly due to relative strip width





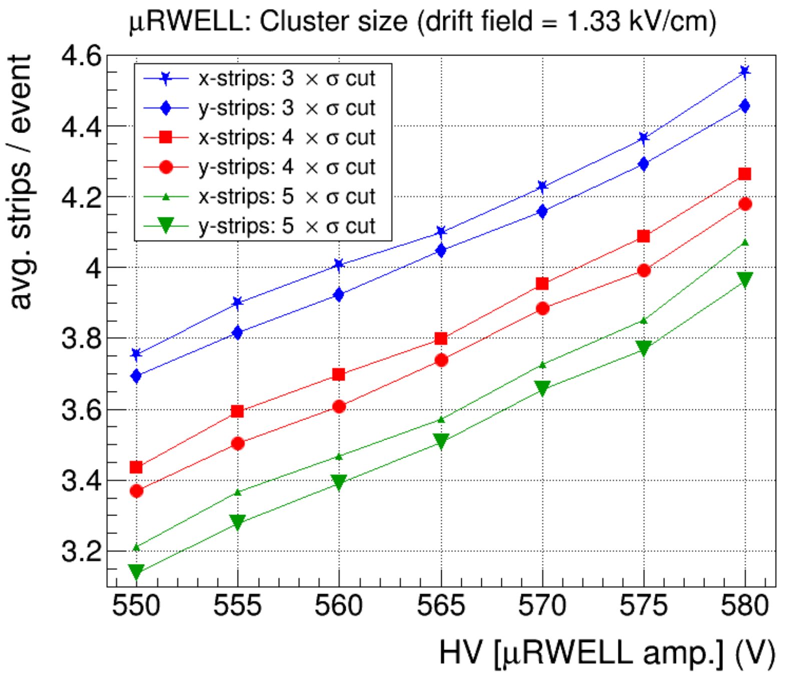


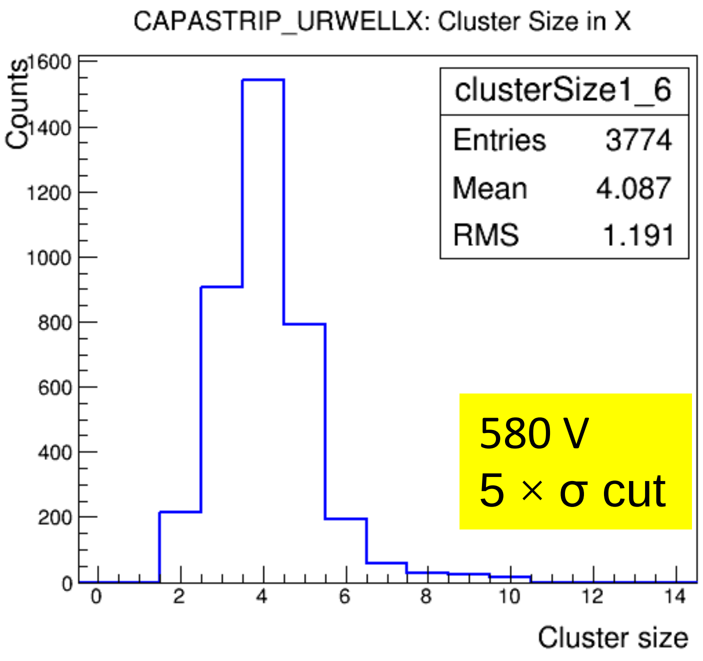


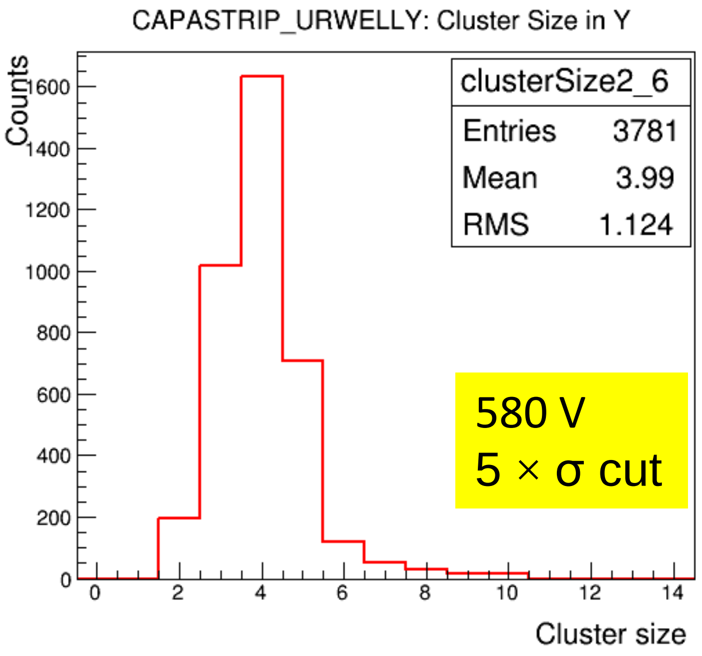
Preliminary results: Cluster size distribution

Capacitive-sharing X-Y µRWELL proto: Cluster size (average number of strips with hits per events

- Average cluster size increases from ~ 3.2 to 4.6 for HV 550 V to 580 V with almost equal cluster size between X and Y strips
- even at lower gain when the signal is significantly reduced (specially for y-strips) cluster size is still large (> 3 @ 550 V)
  - ➔ Make it easier to safely cut off one-strip cluster from cross talk or fake hits during analysis
  - ➔ For these data, efficiency still high > 95% at low gain even when excluding one-hit clusters (see previous slide)
- With capacitive-sharing, the size of the charge cluster does not affect much the cluster size
- Capacitive-sharing readout are singularly suited for **µRWELL and Micromegas** where the charge cloud size of incoming particle is very small

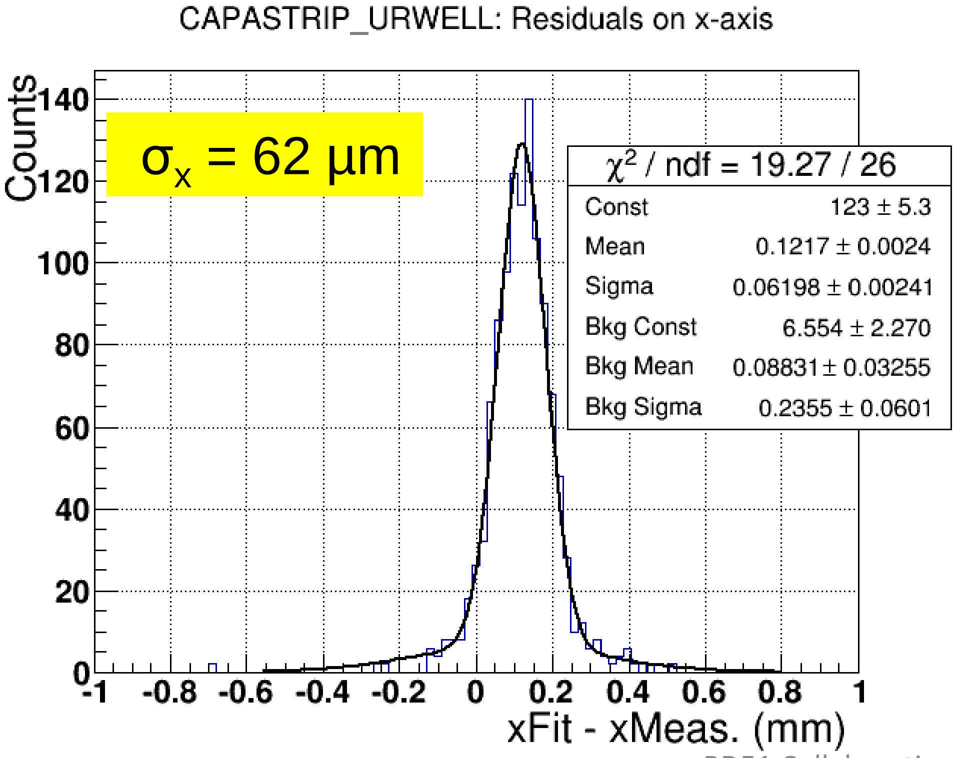


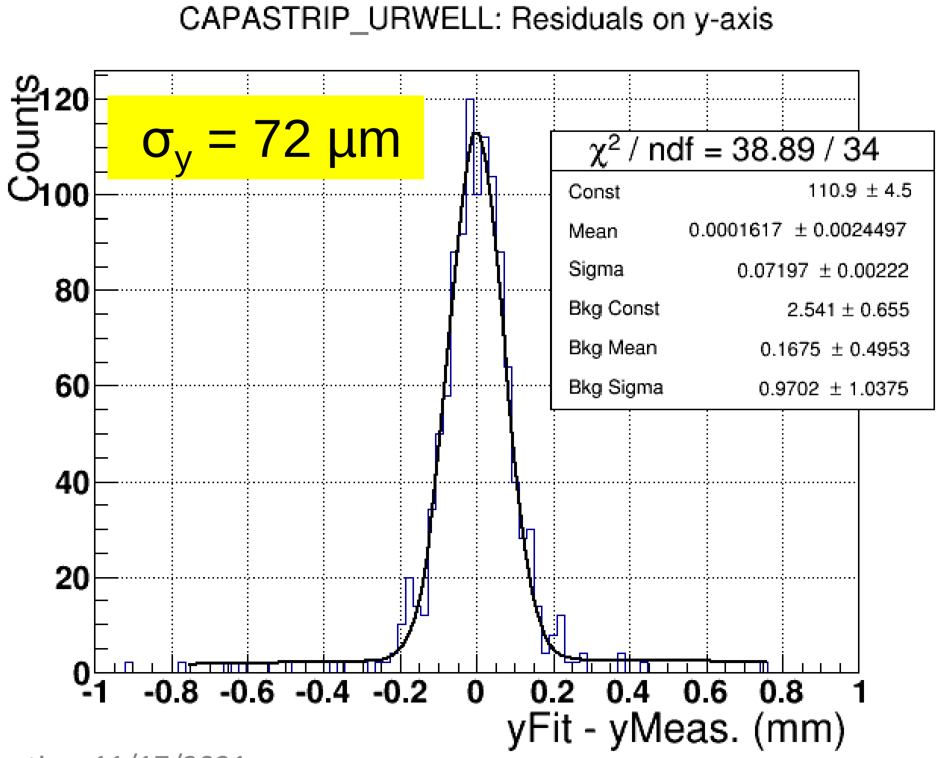




Preliminary results: X/Y Residual distribution from tracking

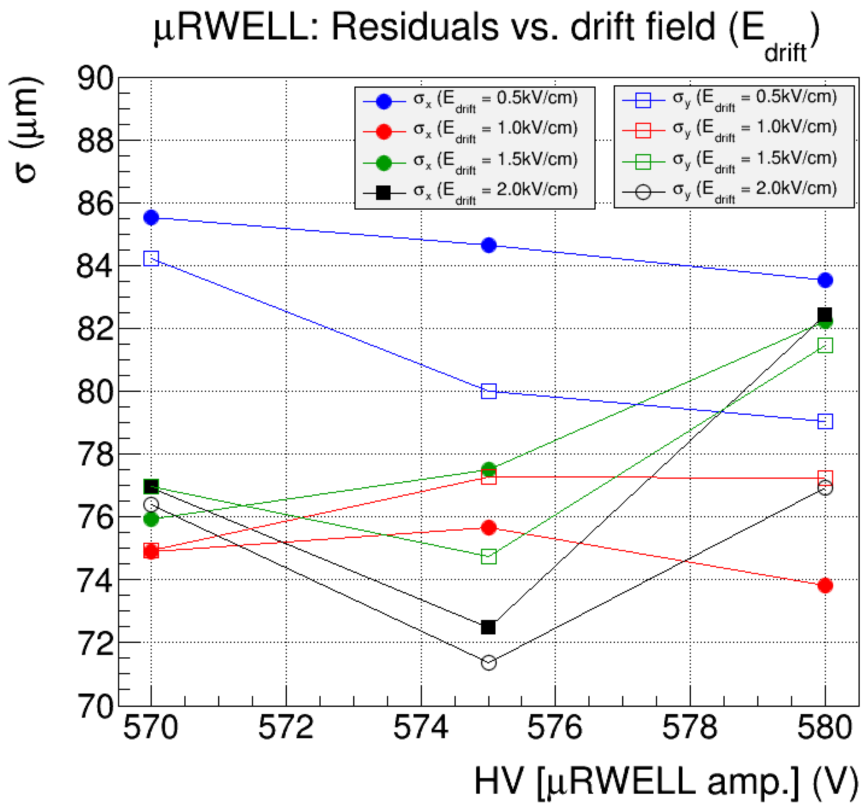
- The plots shown here is not spatial resolution but rather residual from track fit using two COMPASS GEMs for the tracking
- No tracking alignment has been applied to the analysis yet (work ongoing) ➔ these preliminary results are just coming yesterday and today
- But performances are already very impressive and encouraging with 62 µm and 72 µm measured on 800µm x-strips and y-strips respectively
  - Slightly worse for y-strips probably because of the lesser charge ➔ but need to investigate further
  - Expect improvement of these performance after all alignment correction are implemented in the analysis
- Worth to mention that because of the specific feature of capacitive-sharing, similar performance is expected for even wider pitch
  - **Target is 50 µm for 1 mm to 2 mm**

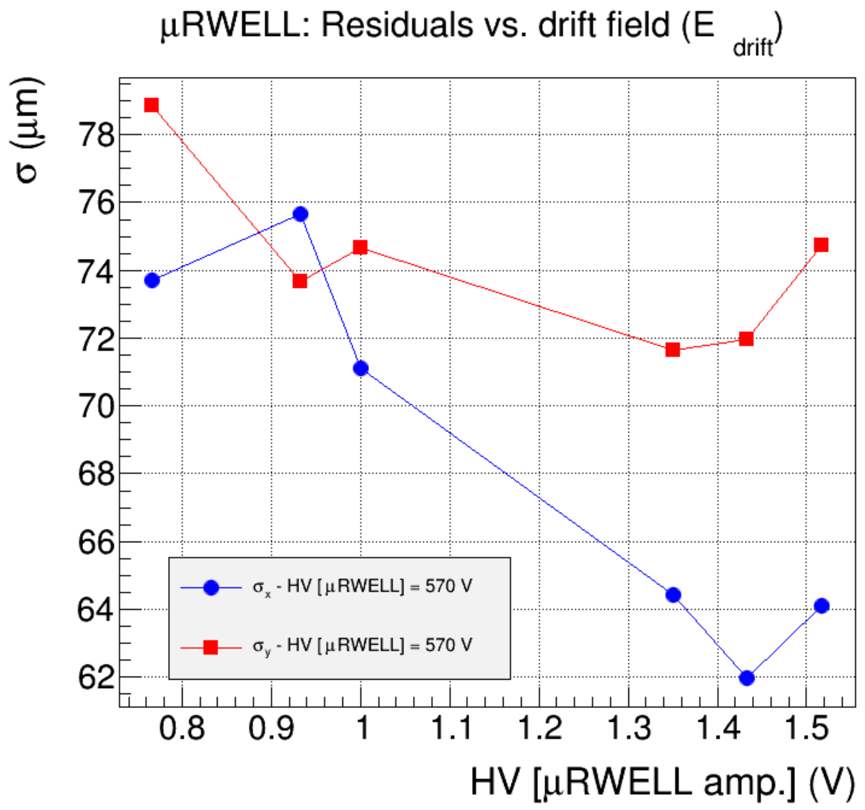




Preliminary results: X/Y Residual vs. HV and Drift field

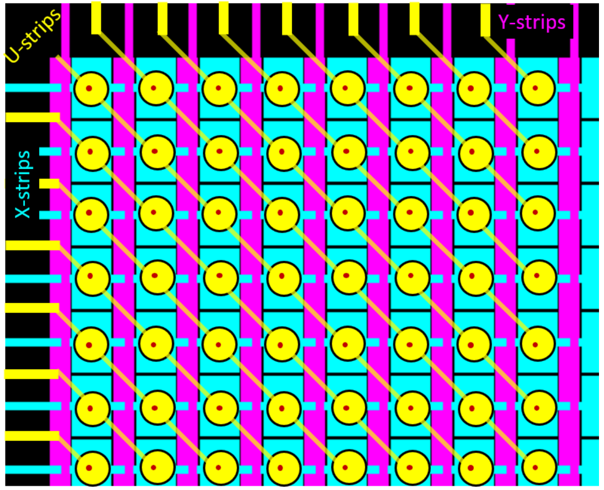
- Again, very preliminary but very little dependence of the spatial resolution (residual) with the gain in µRWELL
- There seems to be however a stronger dependence with the drift field with an optimized resolution for field > 1.5 kV/cm

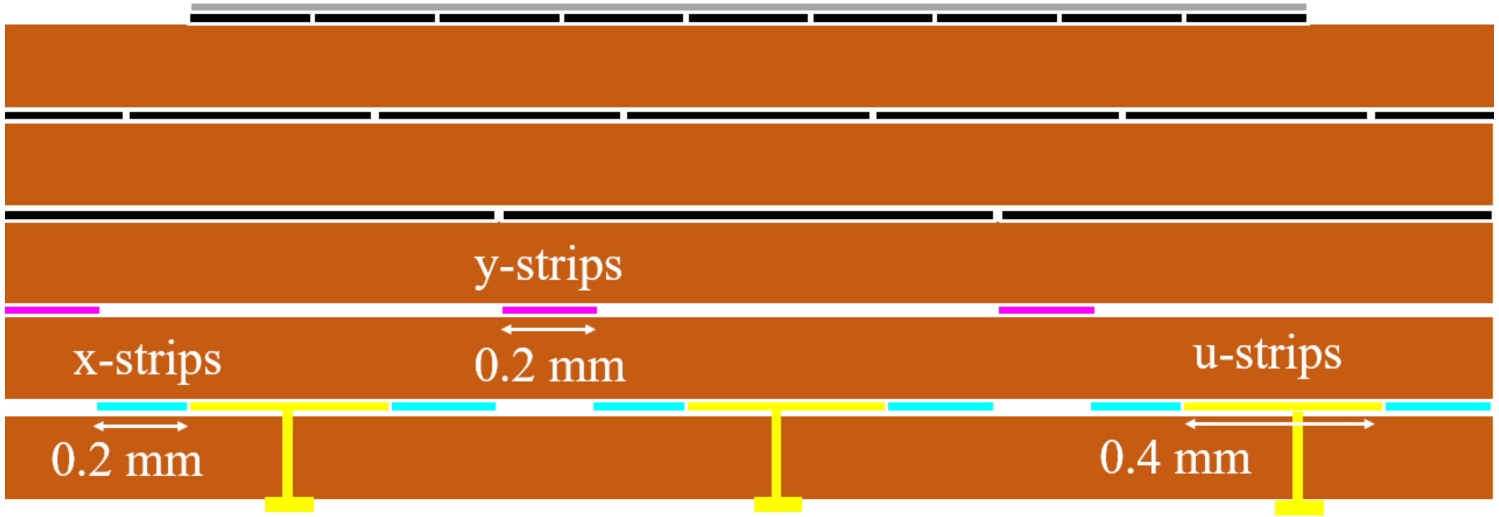




New capacitive-sharing readout structures

New capacitive-sharing structures: 3-axis strips readout





3-axis capacitive-sharing strip readout:

- X-Y-U (C-Z-U for cylindrical MPGD), or U-V-X
  - Address multiple hits (ghost hits) for large detectors
  - Target for spatial resolution ➔ **100 µm in all 3 axis**
- 2-layers configuration for the readout: (cross section sketch below)
  - 1st readout layer (y-strips) ➔ narrow strips
  - 2nd readout layer (x-strips & u-pad-like strips) ➔ wide strip
    - U-pad-like strips connected through vias on a third layer
  - Strip width optimization for equal charge sharing ➔ more iterations
- Design of first prototype with 1-mm pitch ongoing with Rui's team

Alternative 3-layer configuration

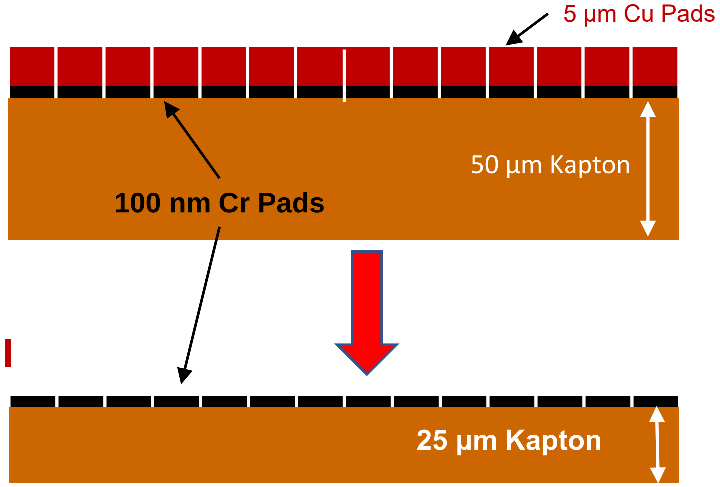
- All 3 X-Y-U strips on 3 different layers
- Simplify fabrication process detectors
- Strip width optimization more challenging
- Lower overall material budget

New capacitive-sharing structures: Low mass – low capacitance

Low-mass (Chromium-based) Cr-Capacitive-sharing readout:

- Replace 5 µm Cu-pad of by the residual 200 nm Chromium pads
  - Cr layer is part base material of the Cu-clad Kapton used for the capacitive-layers ➔ Cu is just chemically etched out
- Thin dielectric layer (12.5 µm Kapton + 12.5 µm glue) instead of 50 µm Kapton + 12.5 µm glue
- Readout strip ➔ Cu-strip ~0.1 mm / Cr-strip 1 mm
  - Narrow Cu-strip in the center of wider Cr-strip for electrical continuity
- Prototype under design in collaboration with Rui's team

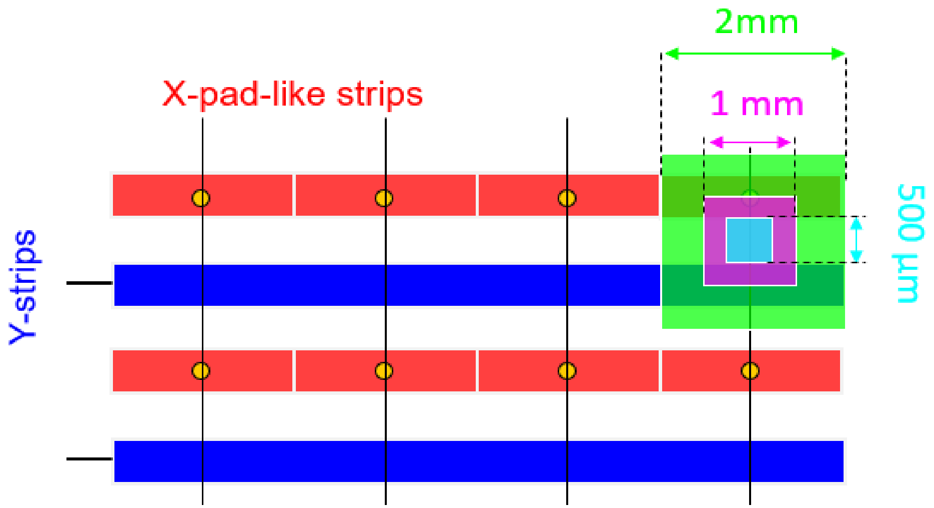
Standard Cu-pads foil
- 5 µm Cu and
- 50 µm Kapton
- 100 nm Cr in between



(Chromium) Cr-pads foil
- 5 µm Cu is removed
- 100 nm pads
- 25 µm Kapton

Low capacitance narrow strip Cr-Capacitive-sharing readout

- Wide strips for large area detector pose the issue of input capacitance for readout electronics
- Capacitive-sharing structures **don't require** wide strips for low channel counts ➔ only wide pitch is required
- Capacitive-sharing structures don't require neighboring strips to be close to each other ➔ wide inter strip gap is OK
- Combined wide pitch with narrow strips to have low channel count – low capacitance – high performances readout structure



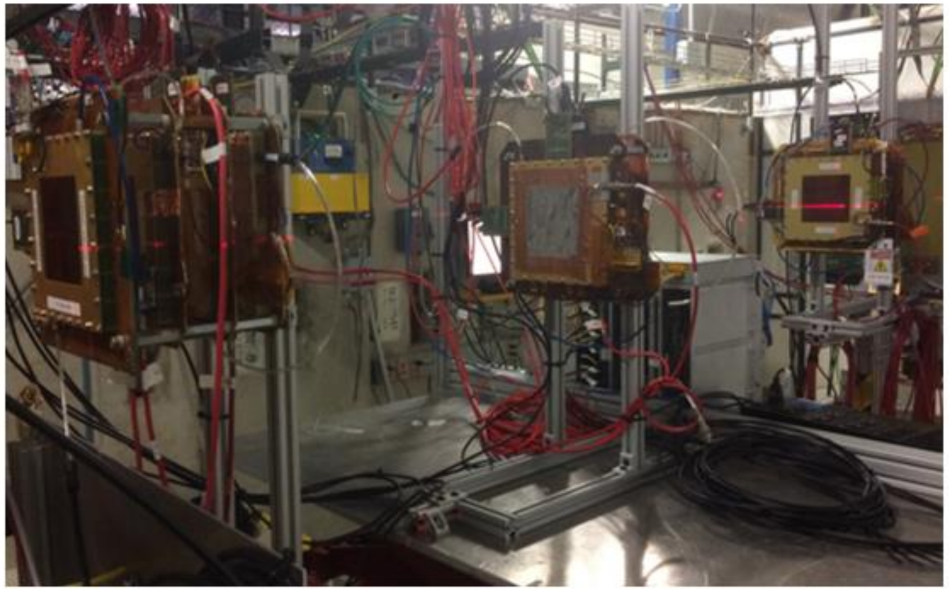
Summary

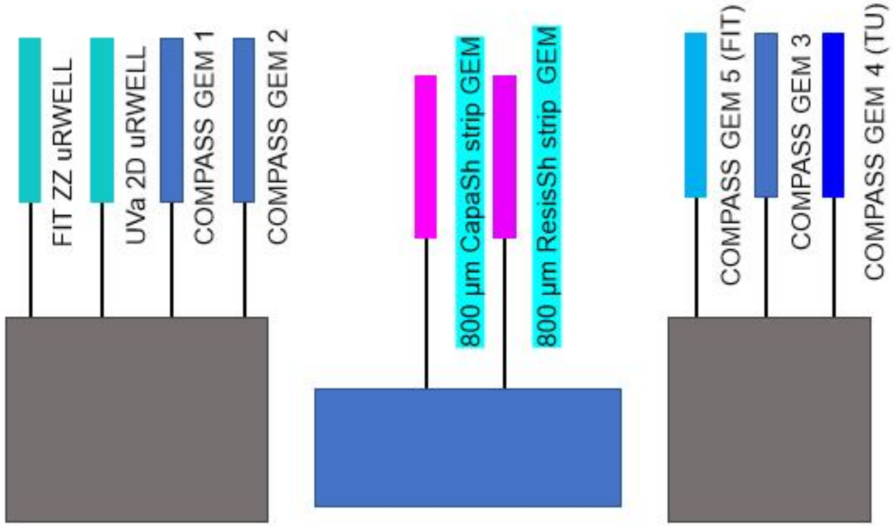
- Capacitive-sharing readout structures: new concept providing excellent spatial resolution capabilities with large readout segmentation (strip pitch or pad size) i.e., low channel count readout solution primarily developed for large area MPGD trackers
- Due to its **simplicity, versatility and flexibility**, capacitive-sharing readout structure are compatible with
  - All types of MPGDs (GEM, µRWELL, Micromegas, THGEM …)
  - All types of readout patterns (2D strips, 3-coordinate (X-Y-U), pad readout, zigzag readout etc ..
- No theoretical limit on strip pitch or pad size achievable with this techniques
  - **< 200 µm** spatial resolution achieved in 2D with 1-cm^2 pad readout
- Several prototypes developed and successfully tested in beam
  - 2D X-Y strips with GEM and µRWELLs
  - Pad readout with different pad sizes
- Preliminary results with 800 um X-Y µRWELL prototype are extremely encouraging
  - **< 72 µm** residual width from coarse track fit analysis (without alignment of the tracking layers performed)
  - Expected better intrinsic spatial resolution closer to 50 µm from refined tracking analysis
- New capacitive-sharing structures under development to address a couple of issues with large area tracking detectors
  - Development of 3-axis (X-Y-U) strips readout structure ➔ addressing multiple hits ambiguity for large area detector
  - Low mass & low capacitance readout devices with Cr-Capacitive-sharing readout structures

Backup

Beam test @ FNAL: May 2021

- Pitch is 800 µm => twice COMPASS design strip
- X and Y strips on different layers separated by 50 µm Kapton but unlike "COMPASS", Kapton not etched out between top and bottom strips
- Signal on top and bottom strip collected through capacitive sharing from the same green pad layer
- But dielectric between green pad layer and bottom strip layer is 100 µm (2 Kapton layers) and 50 µm (1 Kapton layer) for top strip layer
- Therefore, width of top strip (red) 250 µm smaller than width bottom strip (blue) layer 500 µm to compensate for dielectric thickness
- The optimal ration will be studied on the next prototype to be procured from CERN
- Strips optimized to minimize cross talk between top & bottom strips



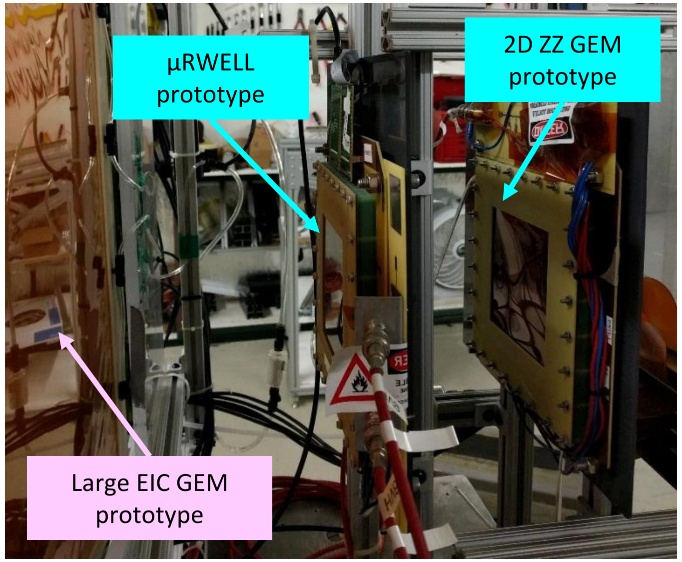


μRWELL prototype with standard 400 um X-Y strip readout

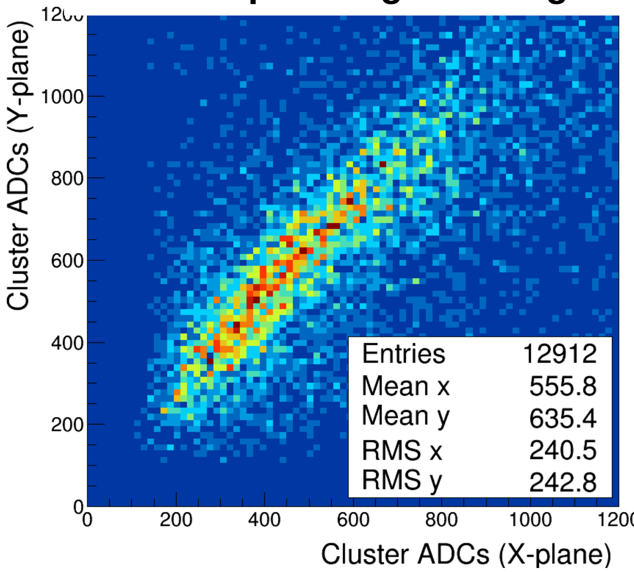
Characteristics of the 10 × 10 cm^2 μRWELL prototype

- **2D (X-Y) strips readout**
  - ⇨ Strips: same pitch (400 μm) as for COMPASS 2D readout
  - ⇨ **X vs. Y charge sharing via capacitive coupling**
  - ⇨ X and Y strip layers are separate by 50 μm glass epoxy layer
- **μRWELL prototype in FNAL test beam**
  - ⇨ Operated with standard Ar-CO_2 (70/30)
  - ⇨ Charge sharing correlation between x and y strips
  - ⇨ Width of track fit residual: 50 μm in x and 43 μm in y
    - ⇨ **Expect even better resolution after track fit correction**

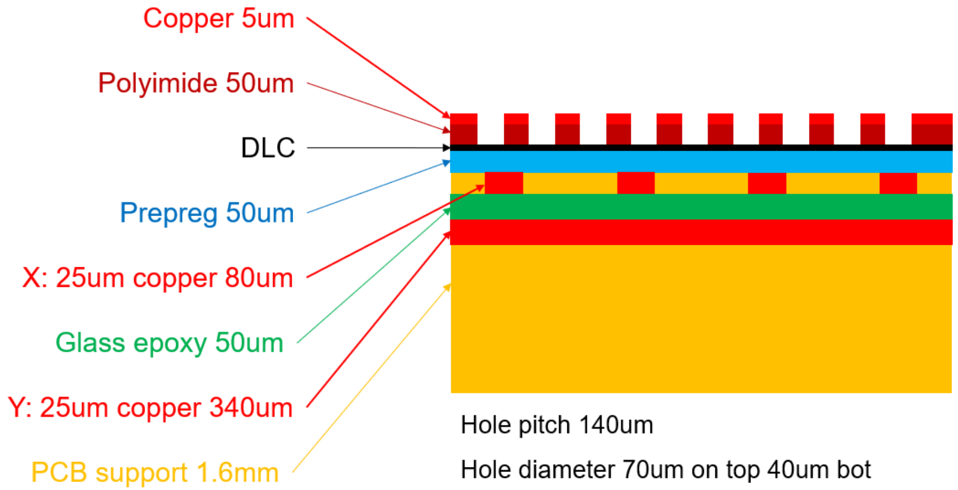
μRWELL at FTBF beam test 2018



X-Y strips charge sharing



Cross section of μRWELL X-Y readout



Hole pitch 140um

Hole diameter 70um on top 40um bot

Read-out line pitch 400um X and Y

Track fit residual distributions from FNAL test beam data (FNAL 2018)